Development of High-Power Microwave Sources Based on Induction Linear Accelerator

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14. ABSTRACT
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Summary

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Time Table
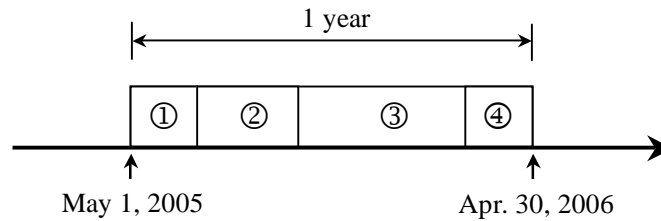
① May 1 ~ June 30, 2005

    Analytical study of antenna-amplifier

    Setup and tuning of induction linear accelerator

② July 1 ~ September 30, 2005

    Design and modeling of antenna-amplifier

    Setup and calibration of microwave diagnostic systems

③ October 1, 2005 ~ February 28, 2006

    Experiments on antenna-amplifier

    Analytical and simulation study of relativistic magnetron

    Setup and tuning of repetitive pulsed power generator "ETIGO-IV"

④ March 1 ~ April 30, 2006

    Experiments on relativistic magnetron

    Analysis of experimental results of antenna- amplifier

List of Conference Papers

1) Numerical Simulations of an X-Band Antenna-Amplifier: Investigations of Gain, Bandwidth, and Drive Frequency Harmonics Generation
   A. Shlapakovski, E. Schamiloglu, and W. Jiang
   2005 IEEE International Conference on Plasma Science, June 2005, Monterey, USA, Paper No. 2P18.

2) High-Power Microwave Generation by Virtual Cathode Oscillator
   W. Jiang, K. Kanbara, S. Ohno, T. Yuyama, and K. Yatsui
   Proc. 15th International Pulsed Power Conference, June 2005, Monterey, USA (to be published).

3) Diagnostics of High Power Microwave Generated by Virtual Cathode Oscillator
   T. Yuyama, K. Hashimoto, W. Jiang, and K. Yatsui
   Prof. 4th Asia-Pacific International Symposium on the Basics and Applications of Plasma Science and Technology, Dec. 2005, Yunlin, Taiwan, p. 367, 2005.

4) Three-Dimensional Particle-in-Cell Simulation of Large Orbit Gyrotron
   K. Naito, W. Jiang, K. Yatsui, M. Kamada, and T. Idehara
   Prof. 4th Asia-Pacific International Symposium on the Basics and Applications of Plasma Science and Technology, Dec. 2005, Yunlin, Taiwan, p. 371, 2005.

5) Development of an X-Band Antenna-Amplifier: Numerical Simulations and Plasma Related Investigations
   A. Shlapakovski, W. Jiang, I. Vintizenko, V. Matvienko, A. Mashchenko, and E. Schamiloglu
   Prof. 17th Int'l Vacuum Electronics Conference, April 2006, Monterey, USA (to be published).

1. Introduction

High-power microwaves are of interest to a variety of applications, especially in space and defense related fields.[1-3] Microwave source development and its applications are studied by the research groups on directed-energy weapons at the Air Force Research Laboratory Kirtland Air Force Base (AFRL/KAFB). Besides the critical issues of microwave power and efficiency, for practical applications, device compactness, durability, and output stability are also considered to be important factors and need intensive experimental studies.

An international collaborative research joint by Nagaoka University of Technology (Japan), Nuclear Physics Institute at Tomsk Polytechnic University (Russia), and University of New Mexico (USA) is being carried out with specific concentration on the improvement of device compactness, durability and output stability of high-power microwave generators. The research activities consist of experimental demonstration of antenna-amplifier by using linear induction accelerators (LIA) and experimental and simulation studies of relativistic magnetrons with improved electrode configurations.

This research report presents the research efforts made by Nagaoka University of Technology and Tomsk Polytechnic University, which are partially supported by Asian Office of Aerospace Research and Development (AOARD). The studies on the antenna-amplifier are covered by Section 2 and the results on relativistic magnetron are presented in Section 3.

2. Hybrid Antenna-Amplifier

2.1 Principle

The concept of the hybrid antenna-amplifier embodies the idea that a compact high-power microwave source might be achieved through the integration of the electron beam accelerator and electrodynamic interaction space with a radiating antenna. Such a possibility exists, in particular, if: (i) a radiating antenna is a dielectric rod surface wave antenna, (ii) amplification is provided due to Cherenkov mechanism of interaction between an annular electron beam and operating mode of this antenna, and (iii) a beam accelerating voltage is generated using an LIA module. Due to the physical principles of LIA operation, its cathode holder is at ground potential from the external side; hence, it can be connected to an external microwave source. As a result, the antenna feed signal, at the same time, serves as a traveling wave tube RF drive. In this device, there is neither a need for a microwave transmission line between the amplifier and antenna, nor for a mode converter providing appropriate field structure for antenna feeding. The benefit added to compactness is the controllability of output radiation characteristics.

This concept has been being explored since 1999.[4-6] In the course of concept exploration, the two characteristic sets of parameters were determined: one providing the dominance of the antenna operating mode and another one exhibiting no dominance and allowing for the drive frequency harmonics generation that makes possible novel tuning schemes (tuning the ratio of harmonic amplitudes in the radiation spectrum). Gain and beam bunching, linear amplifier response and effects of harmonics generation were demonstrated in three-dimensional simulations using the MAGIC code. Also, the design of the LIA module appropriate for driving the device was elaborated, and initial experiments on the annular beam transport in the guiding magnetic field with the dielectric rod inside were performed to clarify whether plasma formation occurs at the rod surface.

In this joint study, the works on the antenna-amplifier development were aimed at the proof-of-principle experiment demonstrating a gain in the device. Efforts were concentrated on the device configuration providing the dominance of antenna's operating mode, the HE_{11} mode, and can be divided into two kinds: (i) designing all details of the future experiment and carrying out MAGIC simulations predicting its expected results and (ii) studies concerning the possibility of plasma formation at the dielectric rod surface located within the annular electron beam. The latter studies include theoretical consideration of the device slow-wave structure with a plasma layer near the rod surface and model experiments on beam transport in the guide magnetic field with the rod inside, aimed at estimating the plasma density.
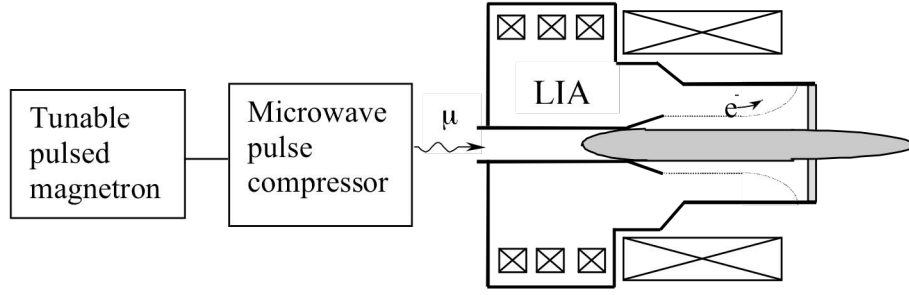
Fig. 1　Schematic of the antenna-amplifier proof-of-principle experiment.

Schematic of the proof-of-principle experiment is presented in Fig. 1.　It is planned to demonstrate a gain at the X-band frequencies. Using the microwave pulse compressor provides the RF drive pulse length shorter than the beam pulse length. This is typical for classical TWT amplifiers and does not take place, as yet, in relativistic ones. The RF drive pulse goes through the transmission system placed within the high-voltage electrode of the linear induction accelerator (LIA) and excites the HE_{11} mode of the dielectric rod, which is amplified in the interaction region by the hollow beam generated in LIA and guided in the magnetic field along the rod.

2.2 Three-dimensional simulations

For the described design of the antenna-amplifier, three-dimensional simulations have been performed using simulation code "MAGIC". The simulation space is depicted in Fig. 2.　The regions of diode, drift tube, and tapered buffer section can be seen. The dielectric rod is inserted inside the conducting cathode. At the left boundary, two ports are set: outer (with respect to the cathode) for the voltage applied, and inner for the microwave input.　The input X-band signal was injected in the fundamental non-axial symmetric TE_{11} mode of the waveguide filled with the dielectric.
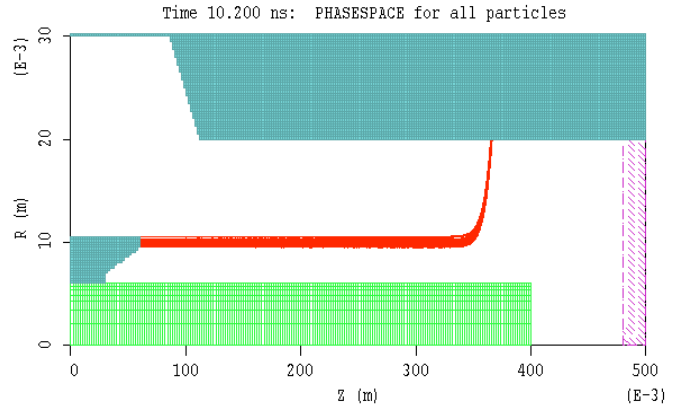

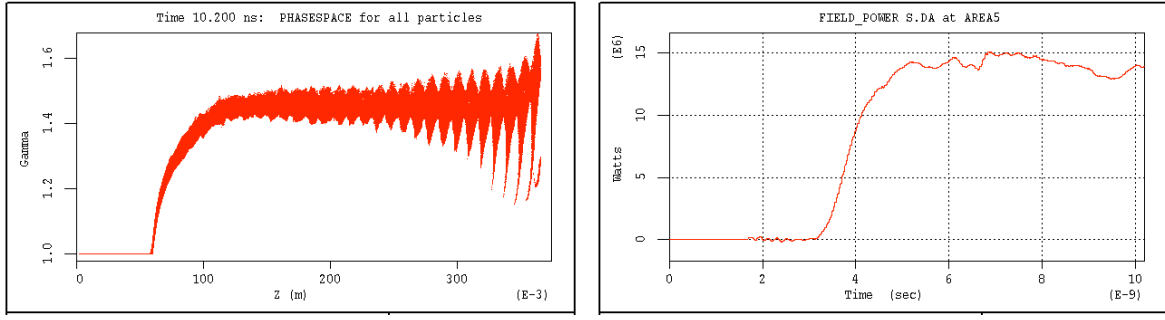Fig. 2　MAGIC simulation geometry and beam axial cross-section.

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Fig. 3　Beam phase portrait (left) and output RF power observed at 1 cm
　　　　before the rod end for ~210 kW RF drive.

In the simulations, the diode voltage of ~290 kV and beam current of ~1.17 kA were provided. The beam was guided by a 3.0 T magnetic field. The achievable gain, bandwidth, and efficiency of the antenna-amplifier were investigated at different values of the input RF power and interaction region length. The peak gain occurs at a 9.3 GHz drive frequency, for which the beam bunching in the non-axial symmetric RF field and the value of gain are illustrated in Fig. 3.　The bandwidth coincides with the tuning range of the available magnetron to be employed for the RF drive pulse generation. Also, the results for gain and bandwidth are in good agreement with those of the linear theory. At the increased interaction region length (by 5 cm) and RF drive power (~530 kW), the device efficiency reaches ~15% at an output power of ~30 MW.
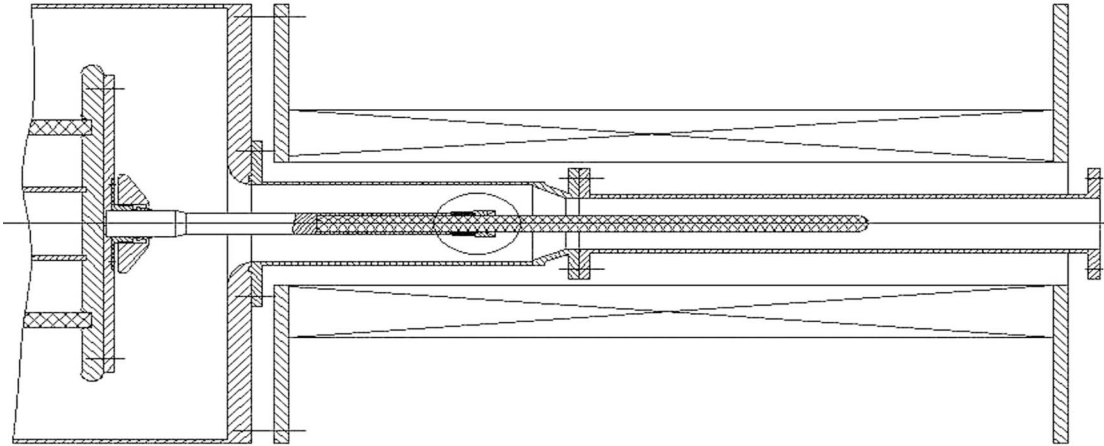

Fig. 4　Schematic of experimental geometry.　The circle marks the
　　　　cathode of magnetically insulated coaxial diode.

2.3 Experimental Setup

The model experiments on beam transport through the antenna-amplifier interaction region in the absence of an external microwave signal were carried out.   Geometry of the experiments is presented in Fig. 4.   It includes the LIA vacuum chamber with its insulator, high-voltage flange, and cathode holder, the coaxial magnetically insulated diode, the tapered buffer section, and the drift tube.   The emitting cathode edge was located in the region of uniform magnetic field (52 mm from the drift tube entrance).   Dielectric rods were inserted through the hollow cathode into the hollow end section of cathode holder. The rods of 400 mm maximum length were used, and the distance from the cathode edge to the rod end was 270 mm.   Radial dimensions corresponded to the design parameters of the interaction region.   Rods of three different materials were tested: plexiglass, polyethylene, and quartz.

The main diagnostic means implemented for estimations of the plasma density near the rod was based on measuring the current transferred by the inside of annular beam. Considering it as the electron saturation current, one can estimate the near-surface plasma electron density n from the formula $j \approx nev_T$, where v_T is the thermal velocity (for surface discharge plasma, typical electron temperature is a few eV), and j is the measured current density.   For measurements, the special composite Faraday cup with two collectors was placed downstream the rod end. The generated annular beam was delivered to its outer collector, and the current inside the beam was delivered to the inner collector through the foil diaphragm. Using diaphragms of different diameters and obtaining dependences of the current delivered to the inner collector on the size of hole allowed for estimating the plasma density radial profile.

It should be noted, at once, that after many shots made in the course of experiments, the plexiglass and polyethylene rods exhibited traces of surface breakdown along all their length from the buffer section to the rod end. In addition, for the plexiglass rod, the small "waist", i.e., 0.3 mm reduction of rod diameter under the cathode edge, has been observed. It is caused, most likely, by the UV radiation from cathode plasma heating the rod up to material transfer off, since plexiglass softening point is as low as 90°C. For the quartz rods, neither breakdown traces, nor waist were observed. Evidently, plastic rods are rather not appropriate for an operating device, and materials with high softening (melting) temperature like quartz, titanium silicate glasses, or ceramics should be employed.

With the quartz rods, the series of experiments were performed, and the current delivered to the Faraday cup inner collector was measured at different accelerating voltages,
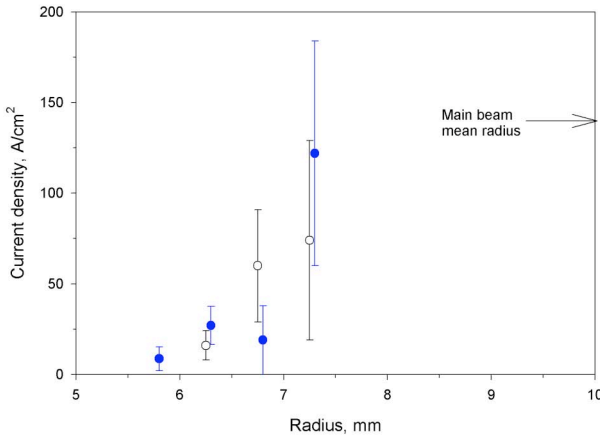
Fig. 5 Estimated current density profiles for 12 mm and 10 mm (in blue) quartz rod diameters. Measured data were obtained at ~280 kV accelerating voltage (~1.1 kA main beam current) and ~2.6 T guide magnetic
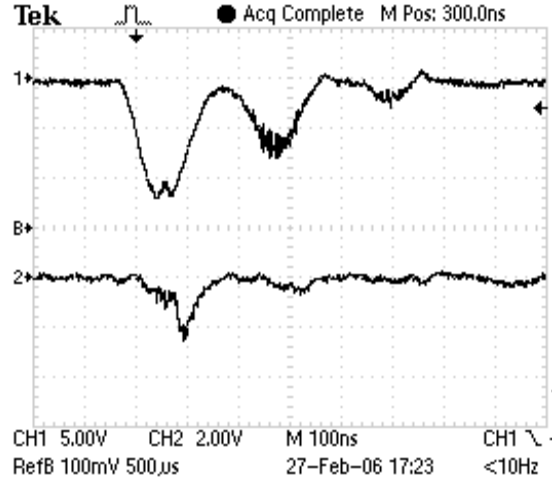
Fig. 6 Traces of current delivered to outer (main beam, channel 1, 450 A/div.) and inner (channel 2, 25 A/div.) collectors of the composite Faraday cup. 12 mm quartz rod diameter, 14 mm diaphragm diameter, ~280 kV LIA voltage, ~2.6 T guide field.

values of guiding magnetic field, and distances between the annular beam and rod surface (the cathode edge diameter was fixed, and varied was the rod diameter). The data were statistically processed to obtain estimations of current density profiles. The typical result is presented in Fig. 5 for two different quartz rods; the gap between the cathode edge and dielectric surface was 4 and 5 mm. The diaphragm diameter was varied from the rod diameter by 1 mm step up to the maximum of 15 mm. Typical oscilloscope traces from the series of LIA shots processed for obtaining the profiles of Fig. 5 are shown in Fig. 6.

It is seen from Fig. 5 that for the larger beam-rod gap, there is a maximum in profile near the rod surface, so that one can associate the following big increase of current density with inner periphery electrons of the main annular beam (current density in the main beam is 1-2 kA/cm^2). The near-surface current density is higher for the smaller beam-rod gap. As to its absolute value, the abovementioned characteristic value of the plasma density, 10^{12} cm^{-3}, corresponds to $j \sim$ 20-30 A/cm^2, so that one can consider the plasma formation is rather acceptable for the data presented in Fig. 5. It has been found in the experiments that the near-surface current density considerably increases with decreasing guide magnetic field and increasing LIA voltage. At the voltage of 320 kV for the rod of 12 mm in diameter, it increases up to 70-100 A/cm^2. Evidently, further investigations are needed with improved vacuum conditions; it is planned to carry out them in the nearest quarter to

achieve acceptable plasma densities over a wider range of LIA voltages and to get better shot-to-shot stability of the plasma density.

3. Relativistic Magnetron

3.1 Thermal regime of the anode block for long-lifetime, high-repetition rate operation

Thermal regime of the repetitive operation of S-band relativistic magnetron has been considered. The objective of this work was to ground the design of the anode block and its cooling system that increases its lifetime. The limitations have been determined for the repetition rate providing operation stability at the given microwave power and pulse length and for the duration of burst admissible at even higher repetition rates. The design of the long-lifetime anode block has been developed, and the hardware is now being manufactured. The demonstration of high-power, high repetition-rate relativistic magnetron operation is planned for 100 to 320 pps at the peak output power of 200 to 400 MW.

We analyzed the main mechanism of the anode block heating, walls bombardment by high-energy electrons, which is much more significant than RF losses in cavities and thermal radiation from the hot cathode. Electrons fall on the anode surface facing the cathode and on the side surfaces of the vanes meeting the rotating spokes. Their motion represents the combination of cycloidal trajectories determined by the crossed E×B fields and radial drift determined by the magnitude of the RF electric field azimuthal component. It means that setting the level of generated RF power and magnetron anode current, one can calculate, for given geometry and applied E×B fields, the kinetic energy of electrons averaged over phases of cyclotron rotation and the power density corresponding to the velocity component normal to the bombarded surface. The said calculations were performed for the NPI LIA-driven magnetron (~300 MW power at ~360 kV operating voltage and ~4 kA anode current) for both vane side surface and cylindrical surface facing the cathode. The division of anode current was taken the same as the ratio of azimuthal lengths of the vane and cavity slot. It turns out that the vane side surface, compared to its cylindrical surface, is subjected to the higher thermal impact (the peak power density $P_0 \approx 5 \cdot 10^6$ W/cm^2) because of higher current density (smaller bombardment area; its height is proportional to the radial drift velocity, which is less than the velocity of spokes rotation) and higher electrons energy ($E_0 \approx 160$ keV).

The following analysis was based on the 1-D heat conduction equation accounting for

the finite depth of heat deposition determined by the range of electrons of energy E_0 in the vane material (heat release over the penetration depth was taken uniform). The vane was modeled as a plate of given thickness, which is exposed, from one side, to the pulsed heat flux of density P_0 and pulse duration τ with the repetition rate f, and at the opposite side, there is a cooling substance providing the heat transfer according to Newton's law with the given heat transfer factor. The solution of the heat conduction equation for the temperature of the exposed surface represents a superposition of the average temperature (growing as if the surface is heated constantly by the average power) and the periodic temperature jumps conditioned by every single pulse. Due to the short pulse duration of the relativistic magnetron (< 100 ns), the temperature jumps do not depend on the plate thickness and cooling at the opposite side. Typical jump values for the stainless steel (the most suitable material for anode blocks to be made of) is of the order of 100 K at P_0 and E_0 corresponding to the parameters of NPI magnetron.

As to the average temperature, it depends on the conditions at the cooled opposite surface. It decreases as the heat transfer factor increases; however, this dependence becomes insignificant at large values, which order of magnitude is determined by the plate thickness. Typically, large enough values of the heat transfer factor (10^3-10^4 W/m^2·K) can be provided by water cooling. Then, the dependence on the thickness becomes important – the thinner plate, the lower temperature, so that it is desirable to reduce the anode block wall thickness as much as possible in the area of electron bombardment.

The time behavior of the temperature at the exposed surface of the 3 mm stainless steel plate is presented in Fig. 7 for the RF pulse duration of 100 ns at different repetition rates and peak power typical for the NPI magnetron operation.   It was
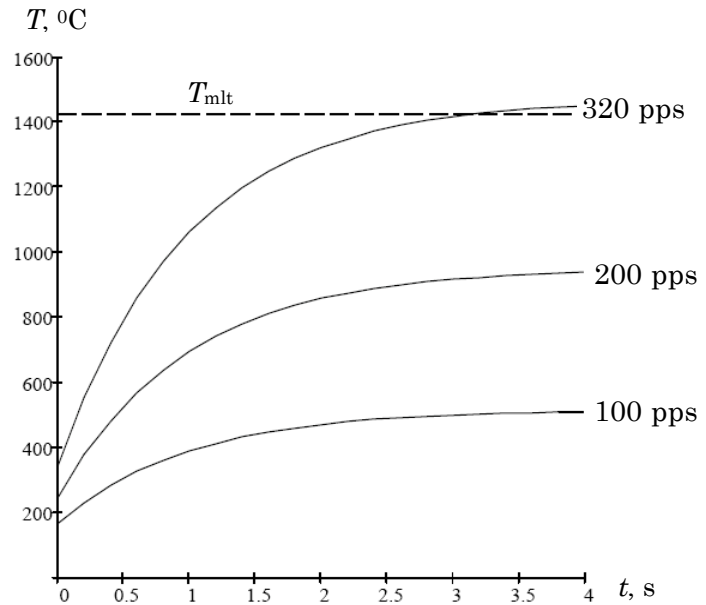
Fig. 7   Temperature of the surface under repetitive pulsed impact vs. time. $P_0 = 5 \cdot 10^6$ W/cm^2, $E_0 = 160$ keV.

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calculated for the heat transfer factor $\alpha = 1.5 \cdot 10^3$ W/m$^2 \cdot$K. From this figure, the limitations are seen imposed on the repetition rate and duration of the burst of pulses. The natural limit is the melting temperature of the material that is shown in the figure as the horizontal dashed line. Also, there is a lower limit conditioned by the requirement of pulse-to-pulse frequency stability (it can change due to the
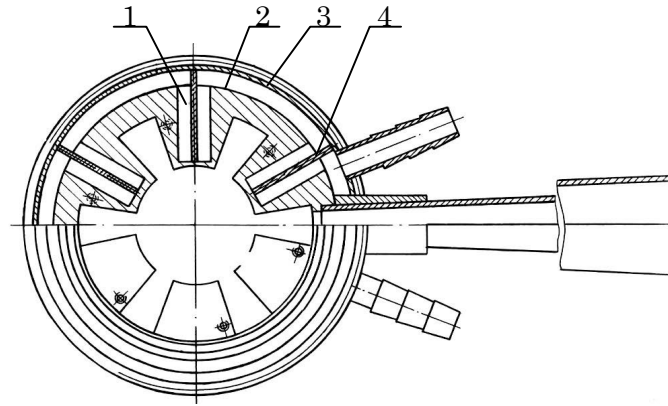

Fig. 8   Relativistic magnetron with the cooling system. 1 – rectangular cavity of the inner cooling contour, 2 – anode block, 3 – coolant jacket, 4 – regulating diaphragm.

vanes thermal expansion). It is seen that the repetition rate of 100 pps allows for, in fact, continuous and stable mode of repetitive magnetron operation providing the peak power of ~300 MW at ~100 ns pulse duration, whereas at 200 pps, generated frequency can be unstable. At still higher repetition rates, the limitation for the admissible duration of the burst of pulses appears; for instance, at $f = 320$ pps, it is of ~3 s.

Schematic of the stainless steel anode block with water cooling that has been designed for a demonstration of long-lifetime, high rep-rate, high-power magnetron operation is shown in Fig. 8. The vane thickness, i.e., the distance between the surface bombarded by electrons and that cooled by running water is 3 mm. The cooling system consists of the outer and inner contours and regulating unit. The inner contour is formed by the rectangular cavities 1 milled in the vanes from the anode block external side. The outer contour is formed by the anode block external surface 2 and the coolant jacket 3. The regulating unit comprises six diaphragms 4 partitioning the outer and inner contours and providing water running through each of the vanes and the possibility to vary the height of water flow in the heated areas. The edges of the vanes are rounded to reduce both static and RF electric fields.

This anode block is presently being manufactured. It is planned to test it and demonstrate the LIA-based relativistic magnetron capability of producing high peak power microwave pulses at the level of average power as high as 5-10 kW.

3.2 Effect of transparent cathode

The so-called "transparent cathode" configuration of relativistic magnetron has been proposed by the research group in University of New Mexico.[7,8] It is featured by the rapid start of microwave oscillation and the potential of high efficiency. These characteristics have been proved by three-dimensional numerical simulations.

In this research, we are trying to carry out the first experimental demonstration of relativistic magnetron with transparent cathode. The repetitive pulsed power generator "ETIGO-IV"[9] located at the Extreme-Energy Density Research Institute of Nagaoka University of Technology is used as the driver for the relativistic magnetron. Figure 9 shows the photograph of ETIGO-IV.

Both conventional and transparent cathodes have been designed for ETIGO-IV with operation voltage of 400 kV and current of 13 kA. Three-dimensional simulations using simulation code "MAGIC" have been carried out to determine the detailed electrode configurations for optimized oscillation mode and frequency. Figure 10 compares the azimuthal electric distribution in magnetrons with conventional and transparent cathode, obtained at resonant frequencies. It is clearly seen that the transparent cathode allows stronger electric field presence near the cathode surface, which is considered to be an important factor for efficiency enhancement.

At this time, the relativistic magnetron experiments are being carried out at Nagaoka University of Technology. The results will be summarized in a few months and are scheduled to be first published at the 3rd Japan-US Symposium on Pulsed Power and Plasma Applications, Aug. 2006.

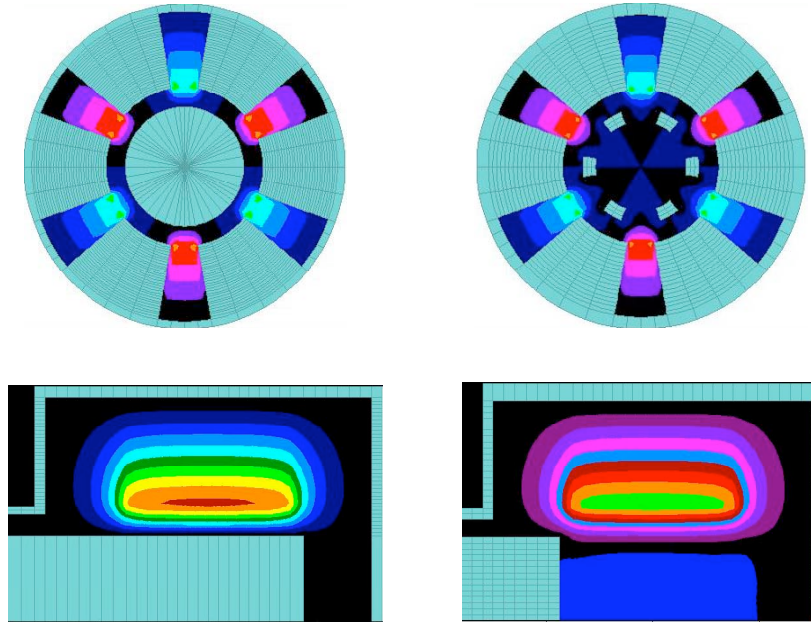Fig. 9   Repetitive pulsed power generator "ETIGO-IV".

Fig. 10 Results of cold-test simulation by using "MAGIC". The colors represent the intensity of azimuthal electric field in magnetrons with solid cathode (left) and transparent cathode (right).

4. Conclusions

1) Analytical results have indicated that the hybrid antenna-amplifier driven by linear induction accelerator is a high-power microwave source with potential compactness and high efficiency.

2) Three dimensional simulations have given X-band microwave output of 30MW in peak power from the antenna-amplifier giving conversion efficiency of ~ 15 %.

3) Experiments on antenna-amplifier have accomplished electron-beam transportation test and dielectric rod material test. Microwave amplification experiments are being continued toward laboratory demonstration of antenna-amplifier.

4) Three-dimensional simulations have been carried out in order to design relativistic magnetron with transparent cathode. The hardwares have been manufactured and the experiments are being carried out, which is expected to be the first experimental demonstration of rapid oscillation start in magnetron.

5) Experimental efforts have been made in developing durable anode electrodes for relativistic magnetrons. The development is toward long-lifetime, repetitive magnetron for high-power microwave generation.

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